US006367263B1

(12) **United States Patent**
Scott

(10) **Patent No.: US 6,367,263 B1**
(45) **Date of Patent: Apr. 9, 2002**

(54) **INTEGRATED CIRCUIT REFRIGERATION DEVICE**

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(73) Assignee: **Intel Corporation**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/583,802**

(22) Filed: **May 31, 2000**

(51) **Int. Cl.^{7}** **F25B 9/00**; F25D 15/00

(52) **U.S. Cl.** **62/6**; 62/259.2; 165/104.26; 165/104.27; 165/104.31

(58) **Field of Search** 62/6, 259.2, 467; 165/104.21, 104.26, 104.27, 104.28, 104.31, 104.32, 104.33

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,165,607	A		8/1979	Fedorowicz et al.	58/50 R
4,679,118	A		7/1987	Johnson et al.	361/386
4,853,762	A		8/1989	Ewer et al.	357/79
4,869,250	A	*	9/1989	Bitterly	128/400
4,916,523	A		4/1990	Sokolovsky et al.	357/74
5,073,116	A		12/1991	Beck, Jr.	439/71
5,097,387	A		3/1992	Griffith	361/385
5,163,551	A		11/1992	Bhatia	206/334
5,282,111	A		1/1994	Hopfer	361/704
5,319,938	A		6/1994	Lucas	62/6
5,329,426	A		7/1994	Villani	361/719
5,331,510	A		7/1994	Ouchi et al.	361/702
5,343,358	A	*	8/1994	Hilbrink	361/700
5,357,404	A		10/1994	Bright et al.	361/818
5,357,757	A		10/1994	Lucas	62/6
5,435,152	A	*	7/1995	McCausland	62/467
5,491,981	A	*	2/1996	Kim	62/324.6
5,515,684	A		5/1996	Lucas et al.	62/6
5,579,399	A		11/1996	Lucas	381/165
5,602,719	A		2/1997	Kinion	361/704
5,621,615	A		4/1997	Dawson et al.	361/704
5,642,262	A		6/1997	Terrill et al.	361/783
5,699,227	A		12/1997	Kolman et al.	361/700
5,801,929	A		9/1998	Cheng	361/807
5,802,707	A		9/1998	Brownell et al.	29/740
5,864,478	A		1/1999	McCutchan et al.	363/147
5,875,095	A		2/1999	Webb	361/700
5,880,524	A		3/1999	Xie	257/704
5,892,293	A		4/1999	Lucas	290/1 R
5,903,436	A		5/1999	Brownell et al.	361/704
5,949,647	A		9/1999	Kolman et al.	361/700
5,949,648	A		9/1999	Liao	361/700
5,982,635	A		11/1999	Menzies et al.	361/790
5,990,549	A		11/1999	Chiu et al.	257/706
5,994,854	A		11/1999	Lawrenson et al.	318/114
6,021,044	A		2/2000	Nevelle, Jr. et al.	361/700
6,046,905	A		4/2000	Nelson et al.	361/704
6,052,285	A	*	4/2000	Hileman	361/699
6,058,013	A		5/2000	Christopher et al.	361/704
6,065,530	A		5/2000	Austin et al.	165/80.3
6,119,474	A	*	9/2000	Augustine et al.	62/259.3

FOREIGN PATENT DOCUMENTS

JP	07-113840	5/1995	G01R/31/26

* cited by examiner

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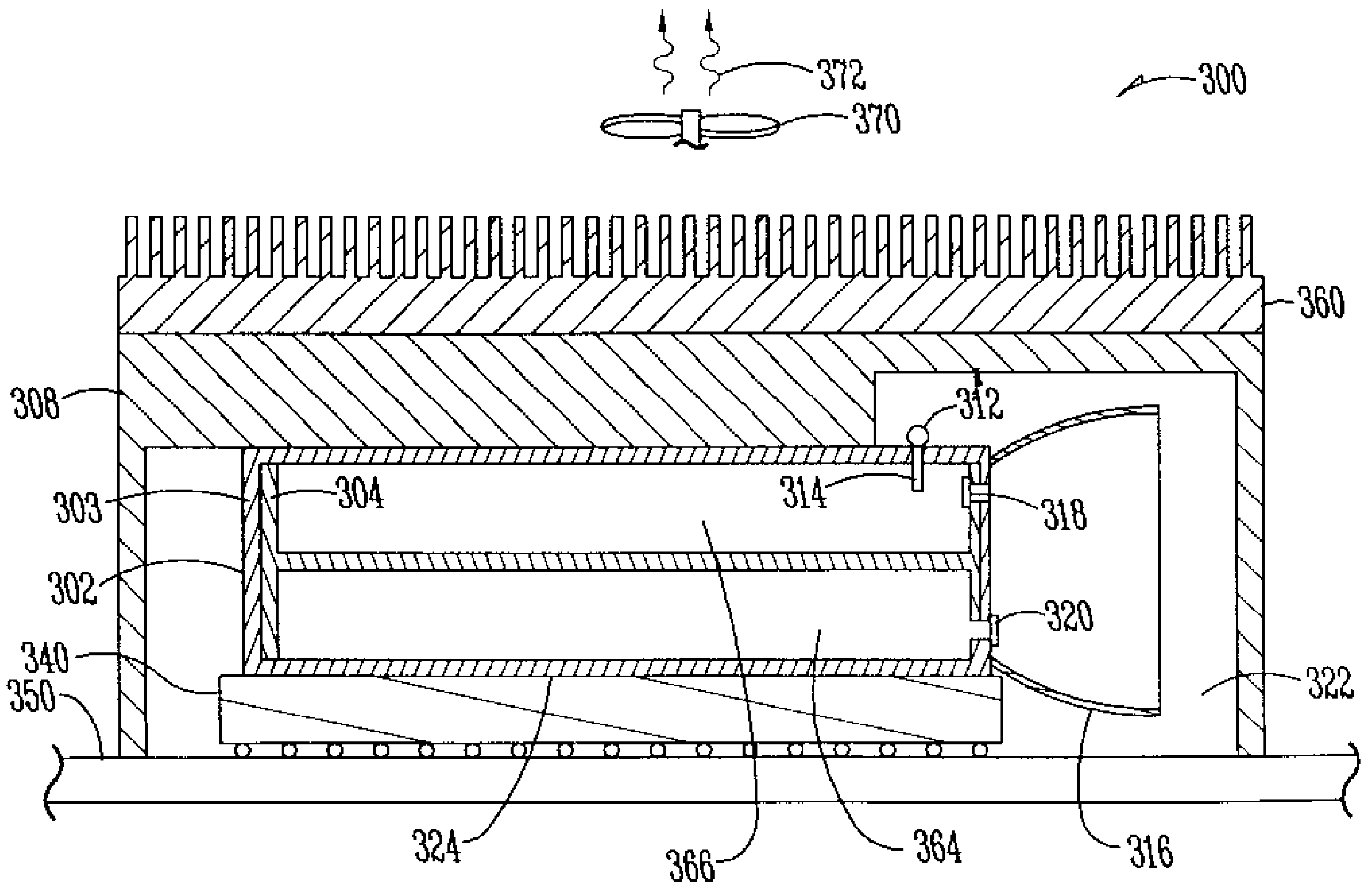
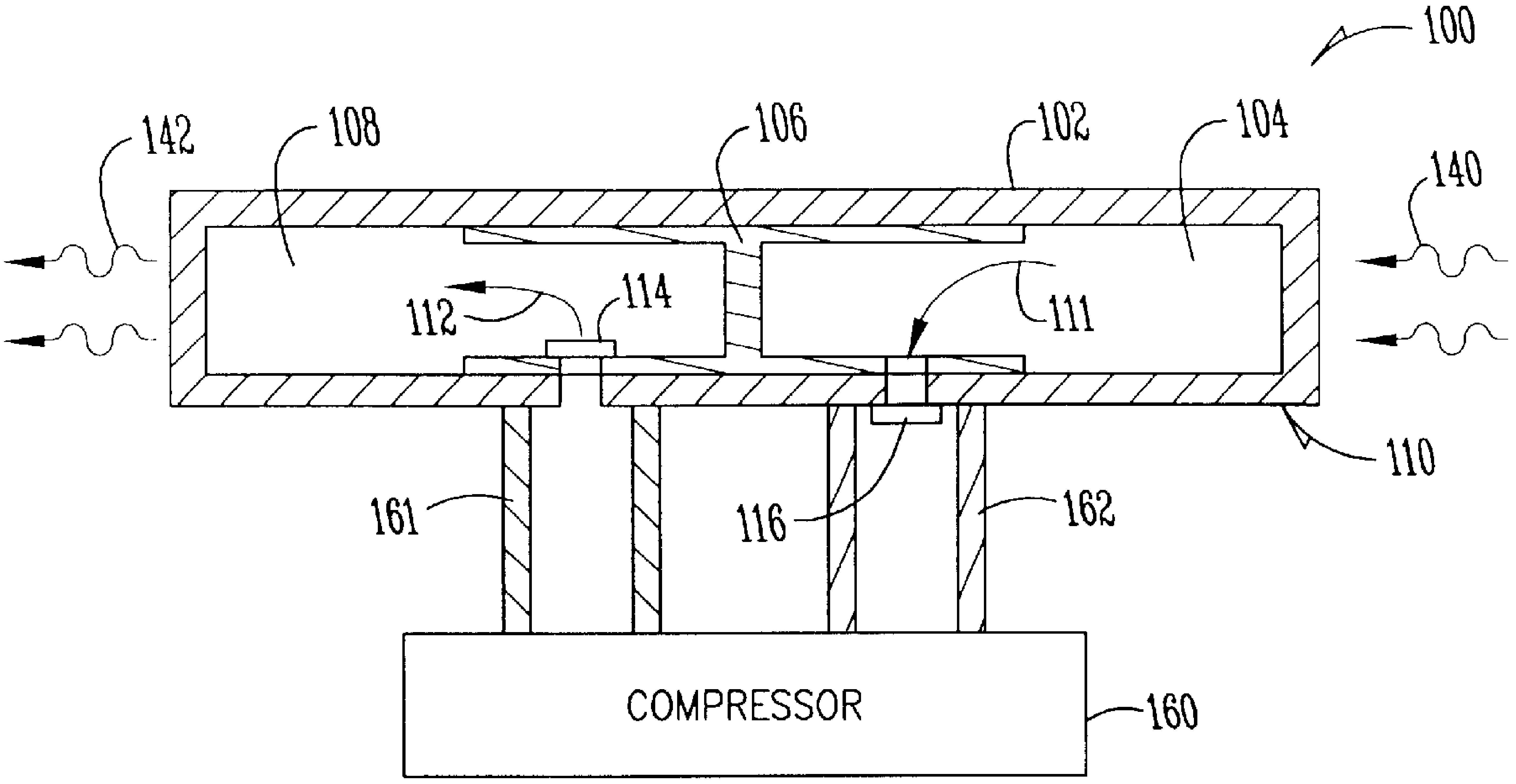
(74) *Attorney, Agent, or Firm*—Schwegman, Lundberg, Woessner & Kluth, P.A.

(57) **ABSTRACT**

A heat pipe includes a flow diverter that separates the heat pipe into an evaporator chamber and a condenser chamber. Each of the evaporator chamber and the condenser chamber are coupled to a compressor with a one-way valve. The compressor receives vaporous working fluid from the evaporator chamber, compresses it, and pumps it to the condenser chamber at a higher pressure and temperature. Within the condenser chamber, the working fluid enter a wicking structure and travels around the flow diverter to the evaporator chamber. The compressor can be an acoustic compressor that includes an acoustic resonating chamber. An integrated circuit package can include the combination of the heat pipe and compressor to create a refrigeration cycle that removes heat from an integrated circuit.

29 Claims, 2 Drawing Sheets




100
142
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104
140
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114
111
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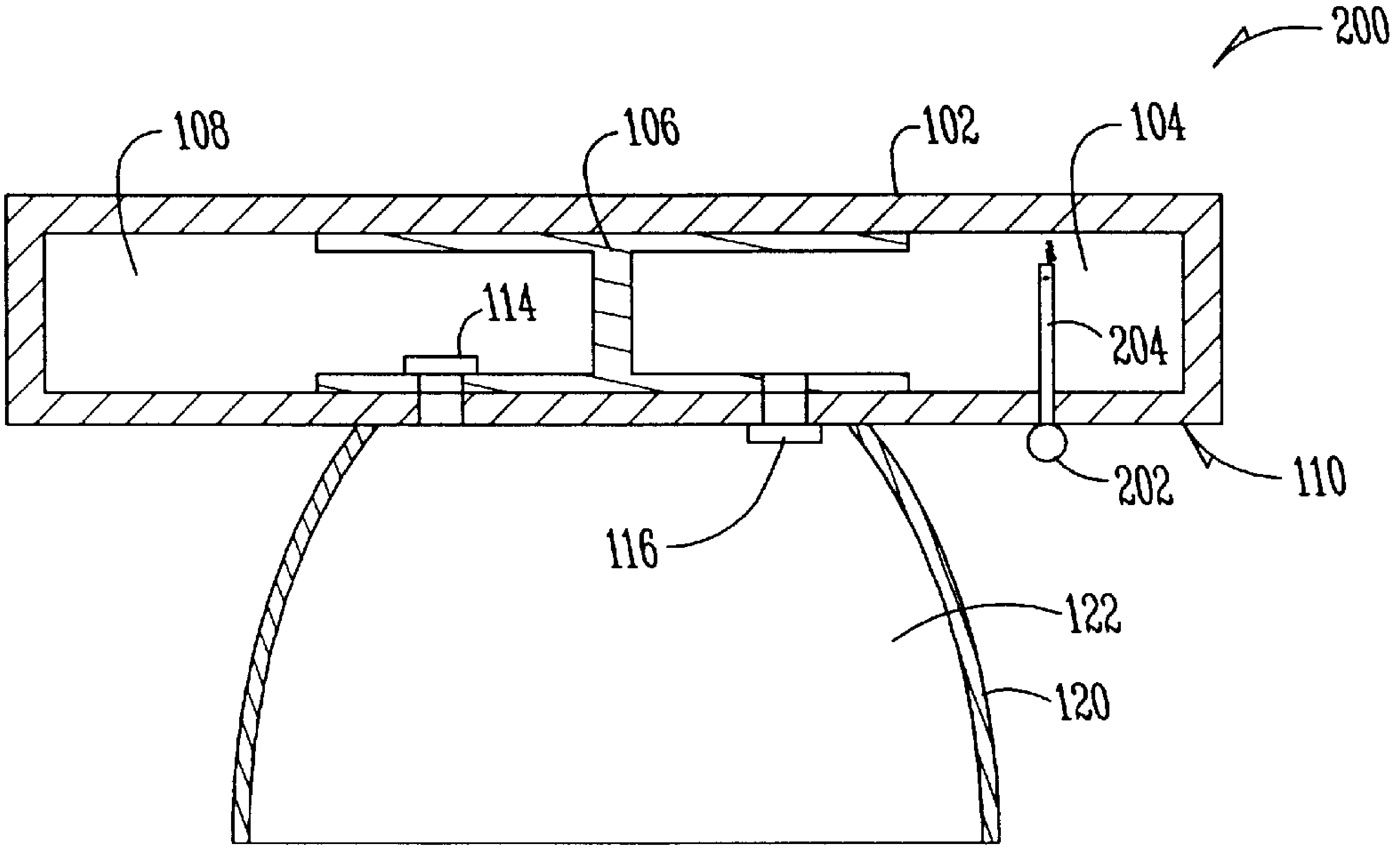
161
116
162
COMPRESSOR
160

Fig. 1


200
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106
102
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202
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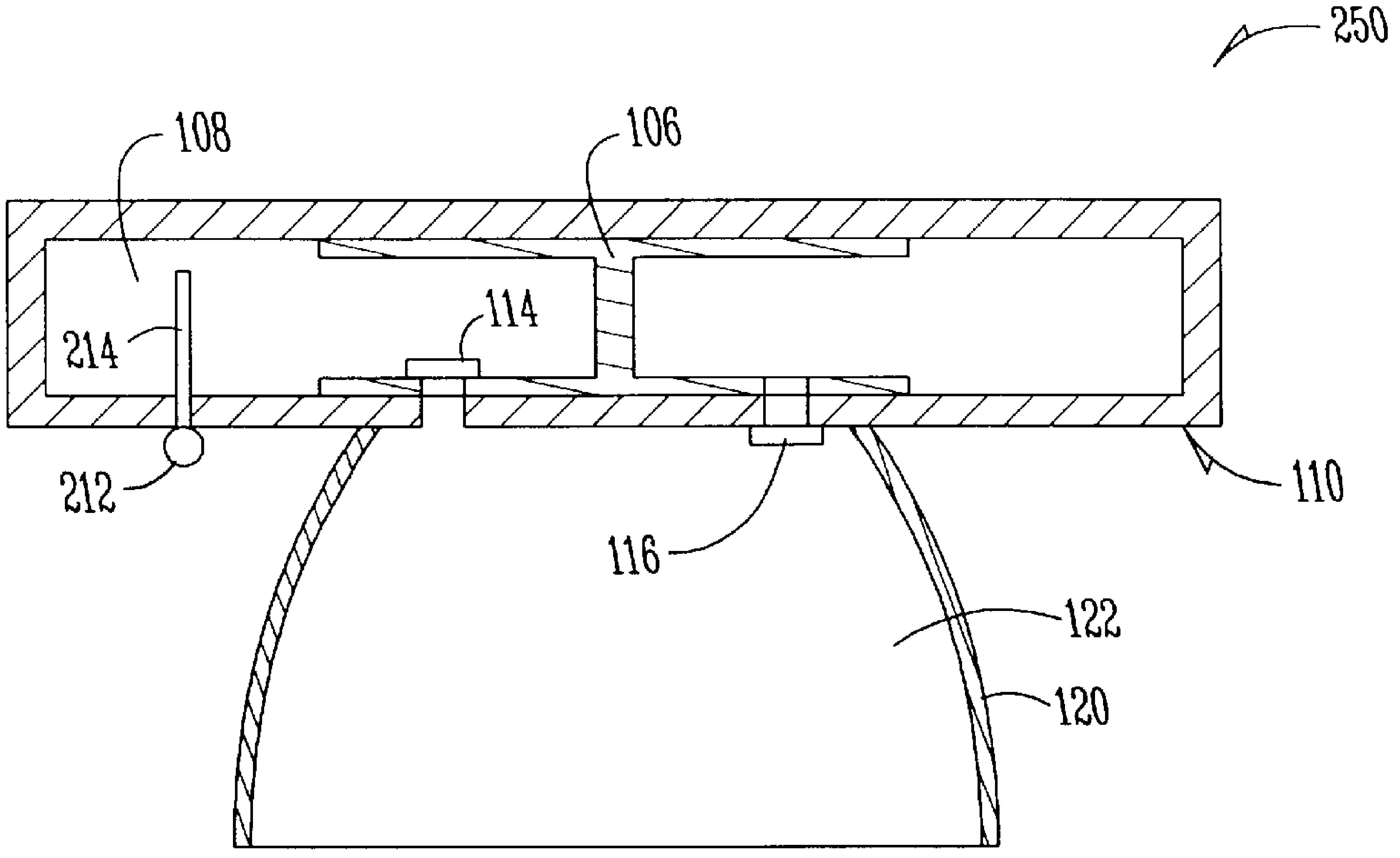
122
120

Fig. 2A


250
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106
114
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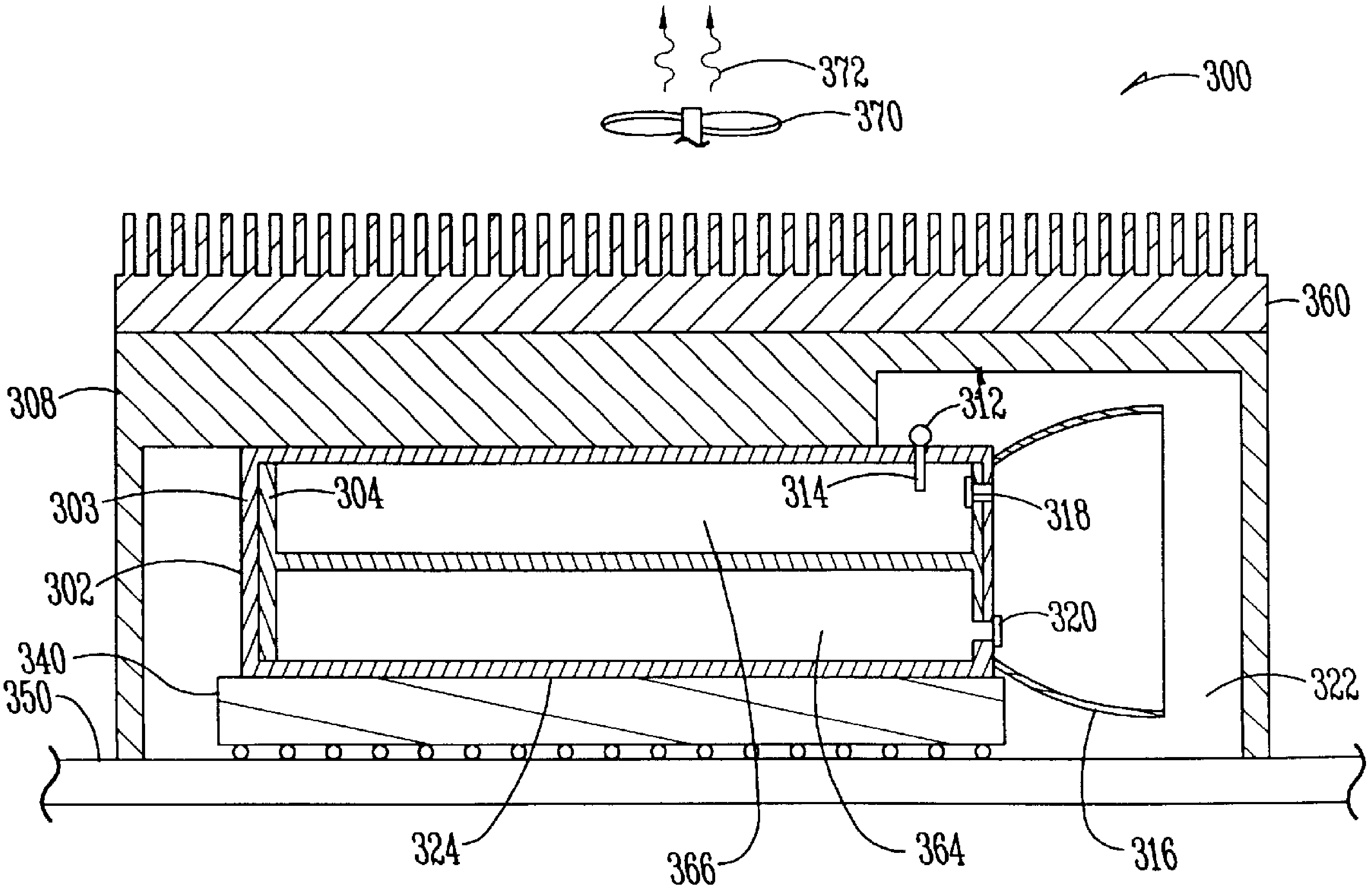
122
120

Fig. 2B


372
370
300
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303
304
314
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302
320
340
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322
324
366
364
316

Fig. 3

INTEGRATED CIRCUIT REFRIGERATION DEVICE

FIELD

The present invention relates generally to integrated circuit cooling systems, and more specifically to integrated circuit cooling systems employing heat pipes.

BACKGROUND OF THE INVENTION

Integrated circuit technology continues to advance at a rapid rate. Advancements include increases in integrated circuit die density which allows for ever-increasing amounts of circuitry in any given die size, and also include increases in speeds at which integrated circuits operate. Higher integrated circuit die densities and increased integrated circuit speeds combine to increase the computational speed in computers and other electronic devices.

Along with increased density and speed of integrated circuit devices comes increased power consumption. State-of-the-art integrated circuits can consume considerable amounts of power, much of which gets dissipated as heat. The problem of increased heat dissipation is exacerbated by the fact that as integrated circuit dice shrink, the amount of heat to be dissipated per unit area of integrated circuit die increases.

Heat is typically dissipated from integrated circuit dice through packages in which they are housed. A surface area of the integrated circuit die is typically thermally bonded to a part of the package for the purpose of dissipating heat from the die. The use of a heat pipe is one known mechanism for transferring heat away from an integrated circuit. A description of a heat pipe can be found in U.S. Pat. No. 5,880,524, issued May 9, 1999 to Hong Xie.

As integrated circuit densities continue to increase, and the associated quantities of heat also increase, the problem of transferring heat away from integrated circuits becomes even more difficult.

For the reasons stated above, and for other reasons stated below which will become apparent to those skilled in the art upon reading and understanding the present specification, there is a need in the art for an alternate method and apparatus to efficiently transfer heat.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a cross section of a refrigeration system employing a heat pipe;

FIGS. **2A** and **2B** show cross sections of refrigeration systems according to multiple embodiments of the invention; and

FIG. **3** shows a cross section of an integrated circuit package.

DESCRIPTION OF EMBODIMENTS

In the following detailed description of the embodiments, reference is made to the accompanying drawings that show, by way of illustration, specific embodiments in which the invention may be practiced. In the drawings, like numerals describe substantially similar components throughout the several views. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the present invention. Moreover, it is to be understood that the various embodiments of the invention, although different, are not necessarily mutually exclusive. For example, a particular feature, structure, or characteristic described in one embodiment may be included within other embodiments. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, along with the full scope of equivalents to which such claims are entitled.

The method and apparatus of the present invention provide a mechanism for generating a refrigeration cycle with a heat pipe. A heat pipe with a wicking structure and a working fluid is divided into two separate chambers by a flow diverter. Each chamber is coupled to a compressor, and each chamber is coupled to the other by the wicking structure in the heat pipe. One chamber is an evaporator chamber and the other chamber is a condenser chamber. The working fluid in the wicking structure adjacent to the evaporator chamber receives heat and evaporates to become a vapor. The vapor is compressed in the compressor and enters the condenser chamber as a vapor. The vapor condenses into the wicking structure, releases heat, and returns to the evaporator chamber.

In some embodiments, the compressor is an acoustic compressor that includes an acoustic resonating chamber. The acoustic resonating chamber has a standing pressure wave set up by a vibrating leaf spring. The vibrating leaf spring can be in the compressor, the evaporator chamber, or the condenser chamber. In some embodiments the leaf spring is made of a piezoelectric material excited at the resonant frequency of the acoustic resonating chamber.

An integrated circuit package employs the refrigeration system to remove heat from an integrated circuit. The result is a compact, efficient, refrigeration cycle device that can remove heat from an integrated circuit under extreme heat conditions.

FIG. **1** shows a cross section of a refrigeration system employing a heat pipe. Refrigeration system **100** includes heat pipe **110** and compressor **160**. Heat pipe **110** includes evaporator chamber **104** and condenser chamber **108** separated by flow diverter **106**. Evaporator chamber **104** and condenser chamber **108** are coupled to each other by wicking structure **102** around the perimeter of heat pipe **110**.

Wicking structure **102** is a porous material through which working fluid can travel from condenser chamber **108** to evaporator chamber **104**. Flow diverter **106** is a solid material that forms a barrier between evaporator chamber **104** and condenser chamber **108** such that a pressure differential between the two chambers can be supported. The working fluid within refrigeration system **100** is a multi-phase liquid that can change between a liquid and a vapor at the operating temperatures and pressures of refrigeration system **100**. In some embodiments, the working fluid is water. In other embodiments, the working fluid is methanol, Freon, or a Freon substitute.

The cross section of heat pipe **110** as shown in FIG. **1** is rectangular, but this is not a limitation of the present invention. Heat pipe **110** can be any shape. For example, heat pipe **110** can be rectangular, cylindrical, spherical, or any other shape useful for a particular application. In some embodiments, heat pipe **110** is shaped to conform to a surface of an item being cooled. For example, heat pipe **110** can be a rectangle of sufficient size to be thermally coupled to an integrated circuit. This is shown in FIG. **3**, and described below with reference thereto.

Compressor **160** is coupled to heat pipe **110** by one-way valves **116** and **114** and tubes **161** and **162**. Compressor **160** can be any type of compressor capable of creating pressure differentials sufficient to operate one-way valves **114** and **116**, and to nearly adiabatically compress the vapor to higher temperature and pressure. In some embodiments, compressor **160** is a continuously rotating device such as a screw compressor or a turbine compressor. In other embodiments, compressor **160** is a reciprocating device, such as a piston compressor. In other embodiments, compressor **160** is an acoustic compressor.

Refrigeration system **100** operates as an integral part of a refrigeration cycle. In other words, refrigeration system **100** includes elements that represent the four parts of a refrigeration device: evaporator, compressor, condenser, and expansion valve. During the refrigeration cycle, working fluid within wicking structure **102** absorbs heat **140** and evaporates into evaporator chamber **104**. The working fluid then travels as a vapor from evaporator chamber **104** through one-way valve **116** and enters compressor **160**. This working fluid flow is shown at **111**. Compressor **160** compresses the vapor to higher pressure and temperature. This compressed vapor enters condenser chamber **108** through one-way valve **114**. This working fluid flow is shown at **112**.

Working fluid within condenser chamber **108** is at a higher temperature and higher pressure than the vaporous working fluid in evaporator chamber **104**. Within condenser chamber **108**, high temperature working fluid enters wicking structure **102** changing phase from a vapor to a liquid and dissipating heat **142** through the wall of heat pipe **110** in the process. Because flow diverter **106** separates evaporator chamber **104** and condenser chamber **108**, and condenser chamber **108** is at a higher pressure than evaporator chamber **104**, the working fluid travels through wicking structure **102** around flow diverter **106** to evaporator chamber **104**. Wicking structure **102** operates as a throttling device in a refrigeration cycle. The working fluid arrives in evaporator chamber **104** at a lower pressure and temperature, ready to receive heat and start the refrigeration cycle once again.

FIG. 2A shows a cross section of a refrigeration system. Refrigeration system **200** includes heat pipe **110** and acoustic compressor **120**. Acoustic compressor **120** includes acoustic resonating chamber **122**, which is coupled to heat pipe **110** by one-way valves **116** and **114**. Acoustic compressors and acoustic resonating chambers are described in U.S. Pat. No. 5,319,938, issued Jun. 14, 1994 to Timothy Lucas. A standing pressure wave within acoustic resonating chamber **122** is produced by leaf spring valve **204**.

Leaf spring valve **204** is an example of a pressure wave creating element. Leaf spring valve **204** vibrates at the resonant frequency of acoustic resonating chamber **122**, and causes pressure waves to develop in evaporator chamber **104**. As a result, one-way valve **116** opens at the resonant frequency of acoustic resonating chamber **122** and causes working fluid to pass therethrough. The action of working fluid traveling through one-way valve **116** sets up a standing pressure wave within acoustic resonating chamber **122**, and the operation of refrigeration system **200** continues substantially the same as the operation of refrigeration system **100**.

Acoustic resonating chamber **122** is shaped such that a small excitation from a pressure wave creating element can create a standing pressure wave that resonates therein. In some embodiments, the standing pressure wave in acoustic resonating chamber **122** is generated with a pressure wave creating element in conjunction with, or in lieu of, leaf spring valve **204**. For example, a standing pressure wave within acoustic resonating chamber can be generated with a piston coupled to an open end of acoustic originating chamber **122**, an electromagnetic shaker, an electromagnetic driver, a spinning device, or the like.

In the embodiment shown in FIG. 2A, leaf spring valve **204** protrudes through the outer wall of heat pipe **110** and wicking structure **102**. Terminal **202** resides on one end of leaf spring valve **204**. In some embodiments, leaf spring valve **204** is made of a piezoelectric material, and vibrates when an electric potential is applied. In these embodiments, terminal **202** includes an electrical contact to which an electric potential can be applied.

Acoustic compressor **120** operates with a standing pressure wave such that the area within acoustic resonating chamber **122** near heat pipe **110** oscillates in pressure from high pressure to low pressure. At points in time where the pressure within evaporator chamber **104** is higher than the pressure in acoustic resonating chamber **122**, one-way valve **116** opens and vaporous working fluid travels from evaporator chamber **104** to acoustic resonating chamber **122**. As the pressure in acoustic resonating chamber **122** near heat pipe **110** increases, one-way valve **116** closes and one-way valve **114** opens. Working fluid then moves from acoustic resonating chamber **122** into condenser chamber **108**. As long as the standing pressure wave is oscillating within acoustic resonating chamber **122**, acoustic compressor **120** continues to pump working fluid from evaporator chamber **104** to condenser chamber **108**.

FIG. 2B shows a cross section of another refrigeration system. Refrigeration system **250** includes leaf spring valve **214** within condenser chamber **108**. As leaf spring valve **214** vibrates, one-way valve **114** opens and closes, and establishes a standing pressure wave within acoustic resonating chamber **122**. The standing pressure wave within acoustic resonating chamber **122** creates an oscillating pressure wave near heat pipe **110**, and the refrigeration cycle operates substantially the same as that of refrigeration system **200**.

FIG. **3** shows a cross section of an integrated circuit package. Integrated circuit package **300** includes substrate **350** and cover **308**. The combination of substrate **350** and cover **308** form cavity **322**. Integrated circuit **340**, heat pipe **302**, and acoustic compressor **316** reside within cavity **322**. Integrated circuit **340** is electrically coupled to substrate **350** and thermally coupled to heat pipe **302** at an integrated circuit mating surface of heat pipe **302**.

Heat pipe **302** includes flow diverter **304** which divides heat pipe **302** into evaporator chamber **364** and condenser chamber **366**, and also functions as a thermal insulator therebetween. Leaf spring valve **314** located in condenser chamber **366** vibrates and causes one-way valve **318** to periodically open, setting up a standing pressure wave within acoustic compressor **316**. When acoustic compressor **316** has a standing pressure wave therein, the refrigeration cycle occurs. The refrigeration cycle draws low pressure vaporous working fluid through one-way valve **320** from evaporator chamber **364** into acoustic compressor **316**, and pumps high-pressure vaporous working fluid through one-way valve **318** into condenser chamber **366**. Heat is transferred to cover **308** as working fluid travels into wicking structure **303**. Working fluid travels around flow diverter **304**, through wicking structure **303** and into evaporator chamber **364**, and the refrigeration cycle repeats.

As previously described, heat travels from heat pipe **302** to cover **308**. Heat continues from cover **308** to heat sink **360** where it is dissipated. In some embodiments, integrated circuit package **300** includes fan **370** to increase airflow across heat sink **360** and to increase heat transfer efficiency. Fan **370** can be a fan fastened to heat sink **360**, or can be a fan fastened to another structure and positioned to create airflow across heat sink **360**.

FIG. **3** shows leaf spring valve **314** within condenser chamber **366**. In some embodiments, leaf spring valve **314** is within evaporator chamber **364**. In other embodiments, leaf spring valve **314** is within acoustic compressor **316**. Leaf spring valve **314** directly produces a standing pressure wave within acoustic compressor **316** when leaf spring valve **314** is within acoustic compressor **316**, and indirectly produces a standing pressure wave within acoustic compressor **316** when in either evaporator chamber **364** or condenser chamber **366**. A standing pressure wave can also be generated with mechanical structures, such as a piston or the like.

Cover **308** is shown thermally coupled between heat pipe **302** and heat sink **360**. In some embodiments, heat sink **360** is coupled directly to heat pipe **302** without cover **308** therebetween. In addition, FIG. **3** shows cover **308** shaped to accommodate acoustic compressor **316** which is shown larger than heat pipe **302** in at least one dimension, but this is not a limitation of the present invention. For example, in some embodiments, acoustic compressor **316** is smaller than heat pipe **302**. Also in some embodiments, leaf spring valve **314** is not located at the top of heat pipe **302**, but is located at a side. In these embodiments, cover **308** can be symmetric such that cavity **322** is a uniform shape.

The method and apparatus of the present invention provides a compact and efficient refrigeration cycle unit capable of removing large amounts of heat from integrated circuits. Previously known mechanisms for generating a refrigeration cycle typically include a separate compressor, evaporator, condenser, and distributed tubing coupling the various components. In contrast, the method and apparatus of the present invention provide a compact unit capable of delivering a refrigeration cycle without the distributed components typically associated therewith.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reading and understanding the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the fall scope of equivalents to which such claims are entitled.

What is claimed is:

1. A refrigeration system comprising:

a wicking structure;

a working fluid in contact with the wicking structure; and

a compressor configured to pump the working fluid, wherein the compressor comprises an acoustic resonating chamber.

2. The refrigeration system of claim **1** wherein the acoustic resonating chamber is configured to be excited mechanically to create standing pressure waves within the working fluid.

3. The refrigeration system of claim **1** further including a flow diverter to create a high pressure condenser chamber and a low pressure evaporator chamber, the high pressure condenser chamber and the low pressure evaporator chamber being fluidly coupled by the wicking structure.

4. The refrigeration system of claim **3** further including a first one-way valve from the low pressure evaporator chamber to the acoustic resonating chamber, and a second one-way valve from the acoustic resonating chamber to the high pressure condenser chamber.

5. The refrigeration system of claim **3** further including a leaf spring valve within the low pressure evaporator chamber, the leaf spring valve being configured to vibrate and create acoustic pressure waves within the working fluid.

6. The refrigeration system of claim **5** wherein the leaf spring valve is comprised of a piezoelectric material.

7. A heat pipe cooling system comprising:

an acoustic compressor having an acoustic resonating chamber; and

a heat pipe fluidly coupled to the acoustic compressor, wherein the heat pipe includes a flow diverter dividing the heat pipe into an evaporator chamber and a condenser chamber, and the heat pipe further includes a wicking structure coupling the evaporator chamber and the condenser chamber.

8. The heat pipe cooling system of claim **7** further comprising:

a first one-way valve that fluidly couples the evaporator chamber to the acoustic resonating chamber; and

a second one-way valve that fluidly couples the acoustic resonating chamber to the condenser chamber.

9. The heat pipe cooling system of claim **7** wherein fluid within the acoustic resonating chamber is configured to be excited by a mechanical apparatus.

10. The heat pipe cooling system of claim **7** wherein fluid within the acoustic resonating chamber is configured to be excited by an electrical apparatus.

11. The heat pipe cooling system of claim **7** further including a piezoelectric pressure wave creating element within the evaporator chamber.

12. The heat pipe cooling system of claim **7** further including a piezoelectric pressure wave creating element within the condenser chamber.

13. An integrated circuit package comprising:

a heat pipe having an integrated circuit mating surface; and

an acoustic compressor fluidly coupled to the heat pipe.

14. The integrated circuit package of claim **13** further comprising an integrated circuit die thermally coupled to the integrated circuit mating surface of the heat pipe.

15. The integrated circuit package of claim **13** wherein the heat pipe includes two chambers, each being coupled to the acoustic compressor by a one-way valve.

16. The integrated circuit package of claim **15** further including a leaf spring valve in at least one of the two chambers, the leaf spring valve being configured to generate an acoustic pressure wave, such that working fluid of the heat pipe leaves one of the two chambers and enters the acoustic compressor at a first pressure, and the working fluid leaves the acoustic compressor and enters the other of the two chambers at a second pressure, the second pressure being greater than the first pressure.

17. The integrated circuit package of claim **16** wherein the heat pipe comprises a wicking structure coupling the two chambers.

18. The integrated circuit package of claim **16** further comprising a heat sink thermally coupled to the heat pipe.

19. The integrated circuit package of claim **16** further comprising a fan thermally coupled to the heat pipe.

20. The integrated circuit package of claim **16** wherein the leaf spring valve is comprised of a piezoelectric material.

21. An integrated circuit cooling device comprising:

a heat pipe having a wicking structure between an evaporator chamber and a condenser chamber;

a flow diverter within the heat pipe, the flow diverter being configured to divert working fluid flow through the wicking structure from the condenser chamber to the evaporator chamber; and

a compressor fluidly coupled to the evaporator chamber and the condenser chamber.

22. The integrated circuit cooling device of claim **21** wherein the compressor comprises an acoustic resonating chamber having a resonant frequency.

23. The integrated circuit cooling device of claim **22** further comprising a pressure wave creating element configured to create pressure waves at the resonant frequency of the acoustic resonating chamber.

24. The integrated circuit cooling device of claim **23** wherein the pressure wave creating element comprises a piezoelectric material.

25. The integrated circuit cooling device of claim **23** wherein the pressure wave creating element is configured to create the pressure waves in the evaporator chamber of the heat pipe.

26. The heat pipe cooling system of claim **3** further including a piezoelectric pressure wave creating element within the low pressure evaporator chamber.

27. The heat pipe cooling system of claim **3** further including a piezoelectric pressure wave creating element within the high pressure condenser chamber.

28. The heat pipe cooling system of claim **8** further including a piezoelectric pressure wave creating element within the evaporator chamber.

29. The heat pipe cooling system of claim **8** further including a piezo electric pressure wave creating element within the condenser chamber.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,367,263 B1
DATED : April 9, 2002
INVENTOR(S) : Scott

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,
Item [56], **References Cited**, U.S. PATENT DOCUMENTS, delete “6/1994 Lucas”, and insert -- 6/1996 Lucas --, therefor.

Column 5,
Line 41, delete “fall” and insert -- full --, therefor.

Column 8,
Line 11, delete “piezo electric” and insert -- piezoelectric, -- therefor.

Signed and Sealed this

Twenty-fourth Day of September, 2002

Attest:

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

Attesting Officer